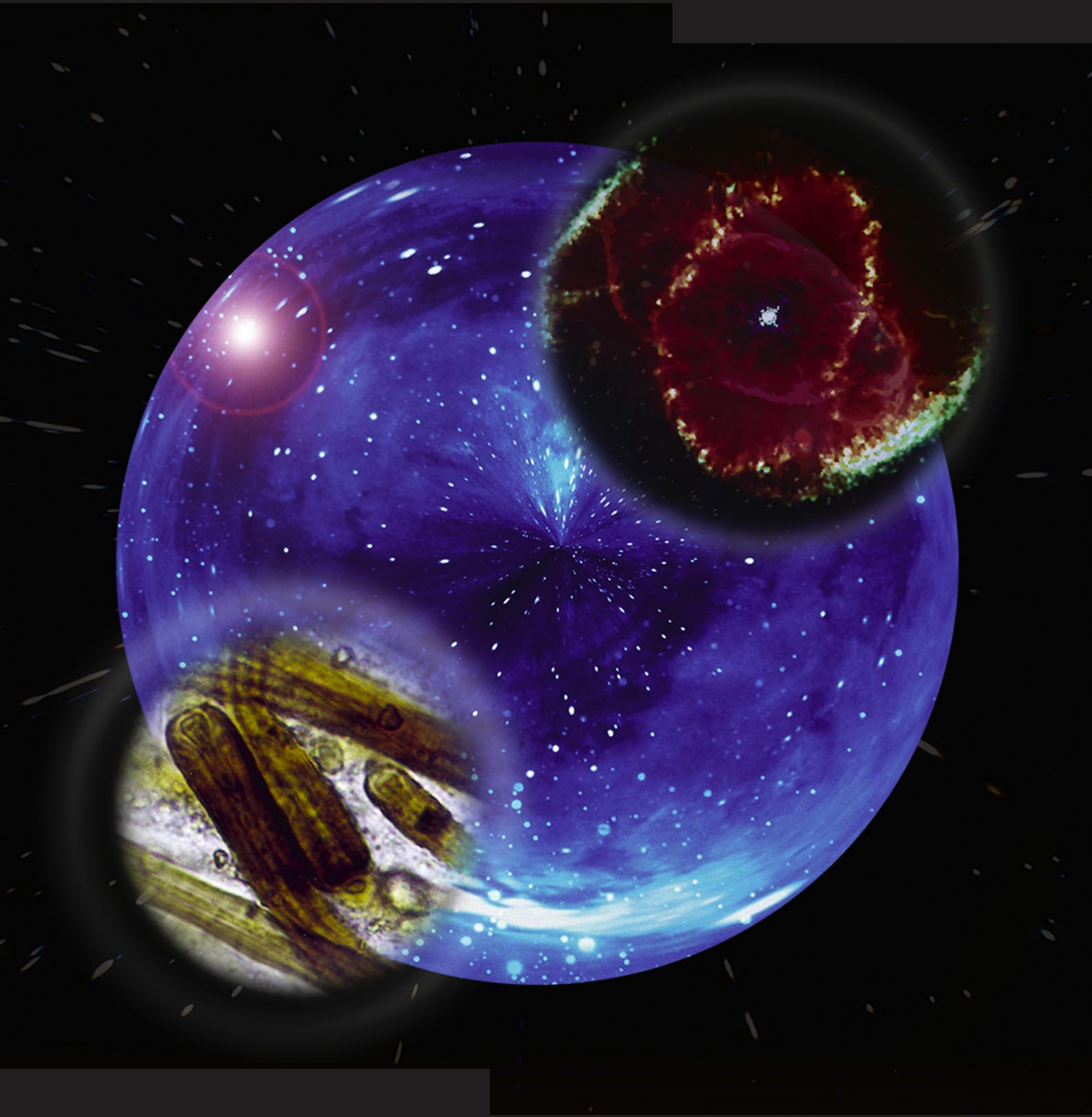


ORIGINS

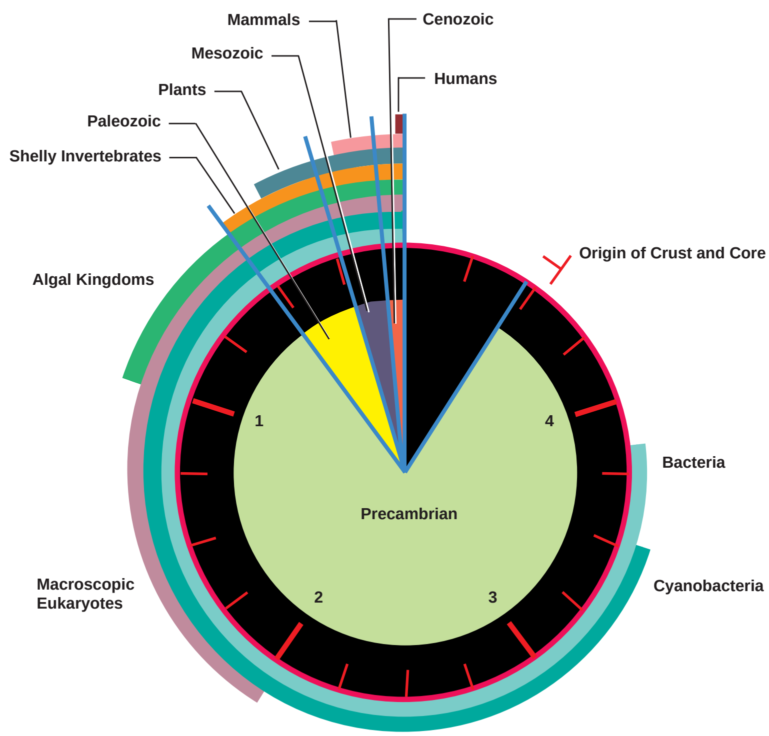
S C I E N T I F I C G O A L S

To comprehend the nature and distribution of life in the Universe beyond Earth, we must understand the origin of habitable planetary environments. Terrestrial life is the only form of life that we know. How did terrestrial life form and how has it persisted for billions of years? We seek the source and nature of the raw materials of life. We wish to understand the cosmic distribution of the environments in which liquid water existed and in which biogenesis occurred.

For the prebiotic Earth, we must understand the origin and chemical nature of the organic and inorganic compounds, the various sources of energy, and the details of the microenvironments from which life arose. We should also consider the possibilities that life formed elsewhere and was seeded onto the developing Earth, and that Earth and Mars are currently exchanging materials. These studies will indicate if a viable natural mechanism exists for spreading life throughout the Universe.

In order to find evidence of life on distant planets and to understand its long-term survival, we must decipher the environmental and biological consequences of the evolution of habitable planets and their biospheres. Scientists can trace the co-evolution of life and the planet by combining evidence acquired from studies of gene history and microbial ecosystems with studies of present and ancient geological environments and their associated fossils. Such studies must include those environmental extremes that define the ultimate limits of life.

4 TO UNDERSTAND HOW LIFE FORMS AND EVOLVES.



The biological clock shows the origins of different life forms on Earth as far back as 3.8 billion years ago.

OBJECTIVE 7 • Determine the general principles governing the organization of matter into living systems.

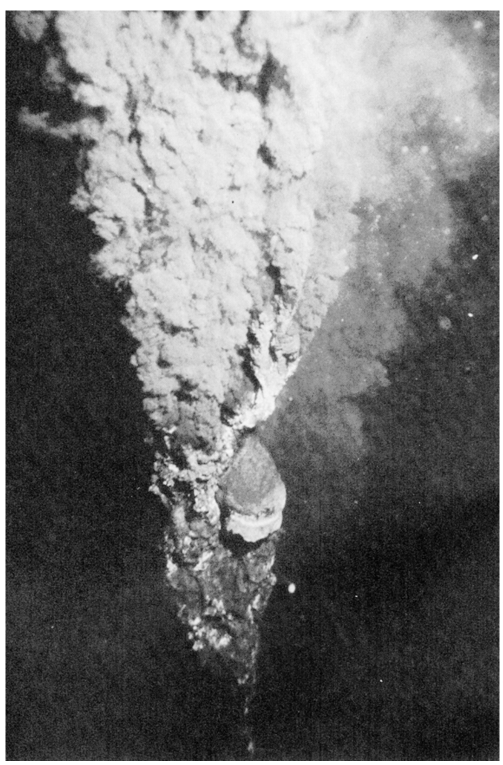
To understand the full potential of life in the Universe, we must establish the physical and chemical principles that lead to the emergence of living systems (defined as systems capable of converting abiotic, non-biological raw materials into biochemically active molecules that produce energy, reproduce, and evolve). Terrestrial life is based on the chemistry of carbon (organic chemistry) moderated by liquid water. Over the past three decades, we have learned that such organic chemistry is common throughout the cosmos. But are Earth-bound biochemical and molecular biological processes the only ones that can support life? The chemistry leading to the origin of life on other planets might well be substantially different from that of the early Earth. Having only one example, we do not know which properties of life are general and necessary, and which are the results of Earth-specific conditions.

INVESTIGATIONS FOR OBJECTIVE 7

Investigation 13: Assess the relative importance of various sources of organic material for the early Earth and their respective roles in the origin of life.

At present, the sources and nature of Earth's primordial organic matter are being debated. Proposed sources include delivery by comets, meteorites, and microscopic interplanetary dust particles; synthesis in the atmosphere; synthesis in warm hydrothermal vents or in geothermal subsurface environments; or some combination of these sources. Each source of organic raw material leads to different predictions about the composition and distribution of the organic starting material and the nature of the earliest pre-metabolic processes leading to the origin of life. We must, therefore, determine the relative contributions of these sources to life's origins on Earth and on habitable planets in general.

We can use data from a number of missions to understand the synthesis of organics in molecular clouds, and their subsequent physical and chemical evolution as they are ultimately delivered to Earth. Missions such as SOFIA, NGST, and FAIR will investigate organics in interstellar dust clouds, while Solar System exploration missions (Stardust and Rosetta) will help characterize the physical and chemical evolution of organics as they are delivered to



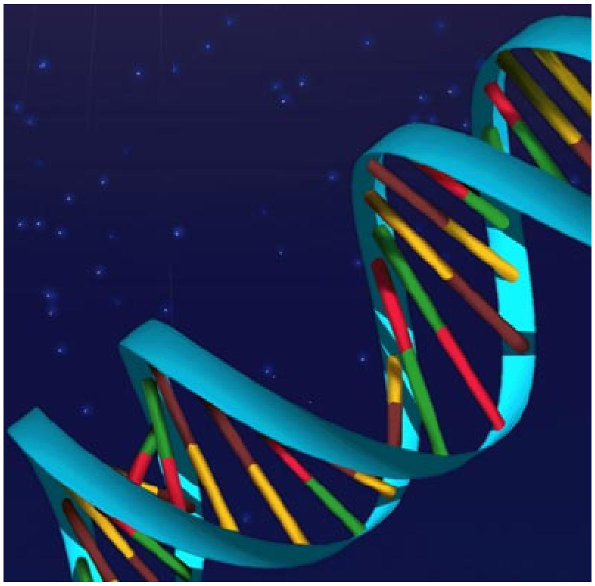
Courtesy of Woods Hole Oceanographic Institution

A volcanic vent located at the ocean bottom emits a wide variety of gases that are incorporated into highly specialized organisms that thrive in this extreme environment.

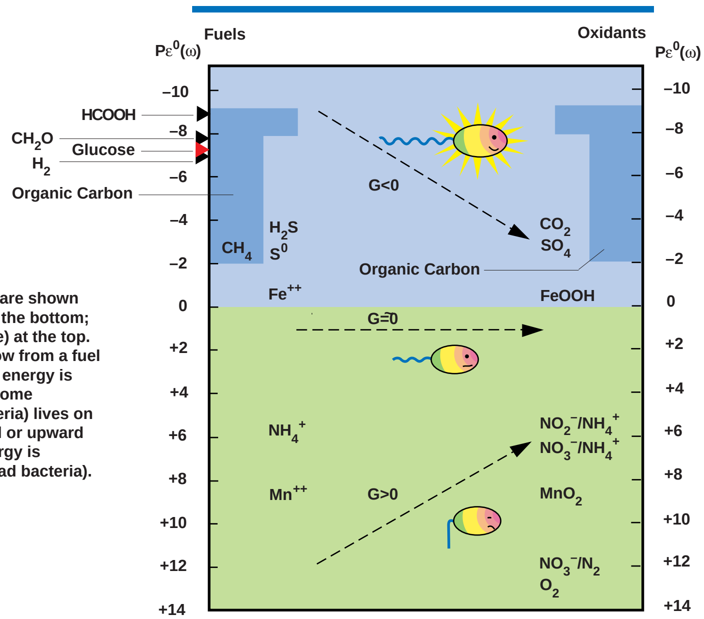
Earth. The combined research will help to determine the chemical structure and the complexity of extraterrestrial organic compounds, as well as constrain the extent to which they contributed to Earth's inventory of primordial organics.

Once adequate concentrations of this organic chemical matter had accumulated, key interactions and reactions would be necessary for the development of life. Realistic laboratory simulations of chemical reactions under various conditions (e.g., other planetary bodies, the surface of the primitive Earth, hydrothermal vents) will elucidate the potential of these reactions to contribute to the formation of biological structures. The geological record can reveal signatures of early life in the form of microfossils, isotope ratios, and mineral assemblages, and provide insight into Earth's atmospheric and mantle chemistry near the time of the origin of life.

Investigation 14: Develop and test plausible pathways by which ancient counterparts of modern cellular components were synthesized from simpler precursors, assembled into protocells, and established replicating catalytic systems capable of evolving.



The architecture of the RNA and DNA molecules links all life on Earth to a common ancestor, but life's origin and subsequent development are poorly understood.



Oxidants to "burn" fuels are shown with the best (oxygen) at the bottom; the worst (carbon dioxide) at the top. A downward-sloping arrow from a fuel to an oxidant means that energy is available, and probably some prokaryote (smiling bacteria) lives on that redox couple. A level or upward arrow means that no energy is available (frowning or dead bacteria).

The thermodynamics of life, with fuels (sources of energy) at left and oxidants on the right. The most energetic (most reducing) fuels are at the top and the least energetic (most oxidizing) at the bottom.

For living systems to emerge from abiotic matter, protocells must have been able to acquire and use energy from the environment, support the synthesis of cellular components (metabolism), and transfer information to succeeding generations (genetics). To explain the origin of life on Earth, it is necessary to demonstrate that these essential functions can be accomplished utilizing only the molecules that may have been available in the protobiological environment. This can be tackled by simultaneously working on two fronts. First, we must conduct laboratory research on chemical pathways leading to the emergence of the macromolecules of life. These pathways should be consistent with the known thermodynamic and environmental constraints present on the early Earth. Second, we must develop models of primitive bioenergetics, replication, and catalysis of the reactions in metabolic pathways, which can be linked via plausible, continuous paths to the same functions in modern organisms on Earth. This work will ultimately lead to the reconstruction of protobiological evolution from a collection of organic molecules to the earliest, unicellular organisms.

After a beginning rooted in elementary chemistry, protocellular systems must exhibit several attributes to be characterized as "living." Foremost among these are their capabilities to replicate, catalyze the chemical reactions of life, integrate their diverse components to act in concert to support these activities, and evolve. To provide essential knowledge about life that may arise beyond Earth, we should build models of cells that exhibit "life-like" properties, using ingredients such as nucleic acids, proteins, membrane-forming molecules, other organic molecules, and possibly minerals. We must also establish the range of conditions under which these cell-like systems can operate.

Through laboratory experiments, self-replicating molecular systems can be developed and characterized. Based on living systems, simple structures should be constructed that are capable of catalyzing biochemical reactions, harvesting biochemically useful energy from the environment, and performing other functions of a living system. In addition, a sophisticated computational research program should be developed to describe and understand self-catalyzing reaction networks, self-organization, and reproduction, as well as the collective behavior of simple biological systems with and without gene control. Ultimately, models of self-replicating, evolving systems will be constructed that can perform the basic functions of a living system and interact with the habitable environments in which they may arise. This work will be conducted under the auspices of the R&A program.

OBJECTIVE 8 • Determine both the early evolution of life and its limits in environments that might provide analogues for conditions on other worlds.

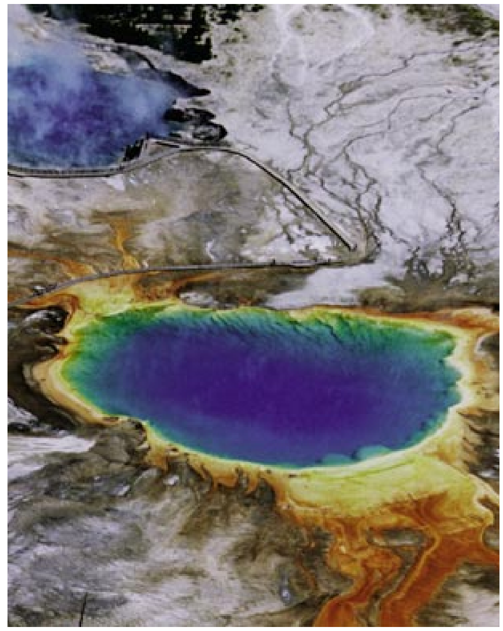
The persistence of life in the Universe depends upon its ability to adapt to evolving planetary environments. An interdisciplinary program must be developed to read the record of life as captured in biomolecules and in rocks (fossils) to identify special chemical interactions between the biosphere and other planetary subsystems. Such a program should also trace the history of Earth's changing environment in response to external driving forces and to biological processes; studies linking planetary and biological evolution will greatly assist our search for distant biospheres.

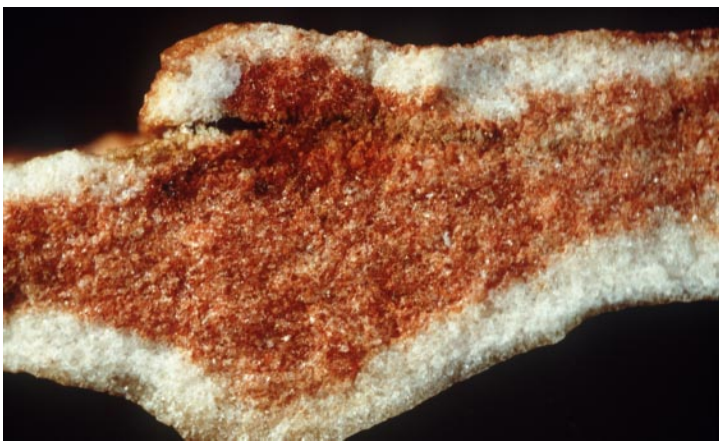
A habitable zone is defined by life's capacity to adapt to extreme environmental conditions. For example, Mars' present habitability is severely constrained by low temperatures, low water potential, and damaging photochemical reactions. The hazards of extreme conditions can be mitigated by biochemical and structural countermeasures within cells, and by processes at the ecosystem level. An effective research program should combine studies of natural ecosystems, physiology, and genetics with the development of new research technologies and missions for the exploration of remote habitable environments — first in our own Solar System and later, beyond.

INVESTIGATIONS FOR OBJECTIVE 8

Investigation 15: Identify the environmental limits for life by examining biological adaptations to extremes in environmental conditions.

To understand the limits of habitability, we must identify and characterize biota in those extreme environments on Earth that are most relevant for a search for life on the closest extraterrestrial bodies thought to harbor liquid water now or in the past (i.e., Mars and Europa). We must also more completely define the range of biochemical strategies for obtaining biologically useful energy. This requires that we define the mechanisms that cells and ecosystems have evolved to survive the extremes in environmental conditions, determine whether biota from extreme environments on Earth could exist in other planetary environments, and define the potential for fossilization and preservation of biota in extreme environments. This research is conducted in the R&A program; it will aid in the selection of sites for exploration, and it will optimize our ability to recognize evidence of life and its fossils.





Primitive life can exist in extreme environments: in highly saline or thermal lakes (above) or within pores in the interior of this Antarctic rock (right).

Investigation 16: Define how the structure and function of microbial communities influence their adaptation, evolution, and detection on other planets.

The diversification, evolution, and survival of early life depended upon efficient coordination of resources and processes by diverse microbial populations. Interdisciplinary studies of microbial communities are required to identify the genetic and environmental factors that contributed to the development of the structures and functions of such ecosystems. We must also document how these communities produce biological markers (biomarkers), which are compounds, structures, minerals, and isotopic compositions that might serve as ecological signatures in rocks or in remotely sensed atmospheres.

Both field and laboratory simulation studies are needed to observe how microbe communities cooperate and compete with each other to harvest energy, capture and retain nutrients, and develop diverse populations. The role of ecological processes in the exchange of genetic information between microorganisms should be documented.

The production of biomarkers should be explored in the context of those communities that serve as analogs for early life on Earth or across the range of habitable environments likely to be explored elsewhere. We must explore the transformations of these biomarkers that occur as they are incorporated into the geologic rock record, or as they are transformed in anoxic atmospheres. This exploration will facilitate the recognition of biomarkers both in geologic samples and during spectroscopic observations of distant planets.